

Demographics of Transition Objects

Joan R. Najita¹, Stephen E. Strom¹ and James Muzerolle²

¹*National Optical Astronomy Observatory, 950 N. Cherry Ave., Tucson, AZ 85719*

²*Steward Observatory, 933 N. Cherry Ave., Tucson, AZ, 85721*

Submitted 2006 November.

ABSTRACT

The unusual properties of transition objects (young stars with an optically thin inner disc surrounded by an optically thick outer disc) suggest that significant disc evolution has occurred in these systems. We explore the nature of these systems by examining their demographics, specifically their stellar accretion rates \dot{M}_* and disc masses M_{disc} compared to those of accreting T Tauri stars of comparable age. We find that transition objects in Taurus occupy a restricted region of the \dot{M}_* vs. M_{disc} plane. Compared to non-transition single stars in Taurus, they have stellar accretion rates that are typically ~ 10 times lower at the same disc mass and median disc masses ~ 4 times larger. These properties are anticipated by several proposed planet formation theories and suggest that the formation of Jovian mass planets may play a significant role in explaining the origin of at least some transition objects. Considering transition objects as a distinct demographic group among accreting T Tauri stars leads to a tighter relationship between disc masses and stellar accretion rates, with a slope between the two quantities that is close to the value of unity expected in simple theories of disc accretion.

Key words: (stars:) circumstellar matter — (stars:) planetary systems: formation — (stars:) planetary systems: protoplanetary disc — stars: pre-main sequence

1 INTRODUCTION

Transition objects are an interesting class of young stellar objects whose properties indicate that significant disc evolution has occurred. Their spectral energy distributions (SEDs) imply the presence of an optically thin inner region (defined by an “opacity hole” of radius $R_{\text{hole}} \sim 1 - 20$ AU) that is surrounded by an optically thick outer disc (beyond R_{hole}). Such an SED indicates that the circumstellar disc has evolved significantly from the radially continuous optically thick disc that is believed to surround all stars at birth.

Transition objects were first identified from the analysis of the SEDs of large samples of solar-like pre-main sequence stars in nearby star-forming regions (e.g. Strom et al. 1989; Skrutskie et al. 1990; Gauvin and Strom 1992; Marsh & Mahoney 1992; Wolk & Walter 1996). They were selected to have SEDs whose long wavelength excesses ($\lambda \gtrsim 10\mu\text{m}$) were equal to or exceeded that expected from a geometrically flat optically thick disc, and whose shorter wavelength excesses were below those of an optically thick disc that extends to within a few stellar radii. Thus the definition included both objects with *no dust* within some disc radius as well as objects with *optically thin* inner dust discs.

Transitional SEDs are expected to arise via multiple pathways. For example, a transitional SED could arise as grains in the inner disc grow into larger bodies, thereby

decreasing the continuum optical depth of the inner disc (Strom et al. 1989; Dullemond & Dominik 2005). Alternatively, as suggested by Skrutskie et al. (1990), a transitional SED may arise through the creation of a large gap, the result of the dynamical isolation of the inner and outer discs by a sufficiently massive giant planet (see also Marsh & Mahoney 1992; Calvet et al. 2002; Rice et al. 2003; D’Alessio et al. 2005; Calvet et al. 2005; Quillen et al. 2004). More recently, disc photoevaporation has been suggested as an explanation for the properties of some transition objects (Clarke, Gendrin & Sotomayor 2001; Alexander, Clarke & Pringle 2006; McCabe et al. 2006). Because all of the above scenarios can in principle produce similar SEDs, additional diagnostic tools beyond the SED may be needed to determine the physical state of a transition object.

To take steps in this direction, we therefore examine in this contribution the demographics of transition objects. Specifically, we compare the stellar accretion rates and disc masses of transition objects with those of accreting T Tauri stars of comparable age. Our methods and results are described in §2 and §3 respectively. The implications of the results are discussed in §4 and summarized in §5.

2 METHODS

2.1 Utility of a Demographic Approach

In order to explore the nature of transition objects, we take a demographic approach, examining the properties of an ensemble of transition objects compared to the properties of a parent population of classical T Tauri stars. Specifically, we compare two well-studied properties of these systems, their stellar accretion rates and their disc masses with those of accreting T Tauri stars of comparable age. A demographic approach has the advantage of being robust against *systematic* errors, since systematic errors (e.g., of the kind described by White & Hillenbrand 2004 and Hartmann et al. 2006) can shift demographic trends up or down in \dot{M}_* or M_{disc} but should not obscure them. Since the use of a large sample of T Tauri stars and transition objects also allows us to “average over” random measurement uncertainties associated with the individual measurements, such an approach may prove useful in identifying demographic trends and, thereby, provide clues to the physical state of transition objects. As a result of significant recent efforts to measure stellar accretion rates and disc masses for young stars, measurements of both quantities are now available for a relatively large number of sources in the Taurus star forming region.

2.2 Stellar Accretion Rates

We adopted stellar accretion rates from the literature, all of which were determined using some measure of the UV/optical accretion excess emission. Stellar accretion rates thus derived are fairly robust. They have been used, for example, to demonstrate correlations between \dot{M}_* and stellar mass (e.g., Muzerolle et al. 2003; Natta et al. 2004) as well as \dot{M}_* and age (e.g., Sicilia-Aguilar et al. 2005).

Stellar accretion rates (Table 1) were adopted from the following references, in order of preference: Gullbring et al. (1998, hereafter, G98); Hartmann et al. (1998, hereafter, H98); White & Ghez (2001, hereafter, WG01); Calvet et al. (2004); Gullbring et al. (2000); Hartigan, Edwards & Ghandour (1995, hereafter, HEG95). Values from WG01 were used for all binaries when available, since their observations were specifically tailored for resolving most binary systems. Systematic differences between some of these determinations arise from several factors, including different extinction estimates, bolometric corrections, and pre-main sequence tracks adopted to estimate stellar masses. We have thus attempted to place all the values on a consistent scale by calculating any systematic offsets for objects with measurements in common with H98 (which includes all values from G98).

We show two such comparisons with measurements from WG01 and HEG95 in Figure 1. One can see in both cases a similar trend with a relatively small dispersion of ~ 0.2 dex, which is, perhaps surprisingly, smaller than the typical ~ 0.5 dex measurement uncertainties discussed by G98 and the typical veiling variability of a factor of 2 or less (e.g., Hartigan et al. 1991). However, there are significant systematic offsets. The WG01 values are lower on average by a factor of 2. Since they use the same methodology as H98, most of the offset is likely a result of their adoption of a different set of pre-main sequence tracks (Baraffe et al. 1998; Palla & Stahler 1999) which give systematically higher

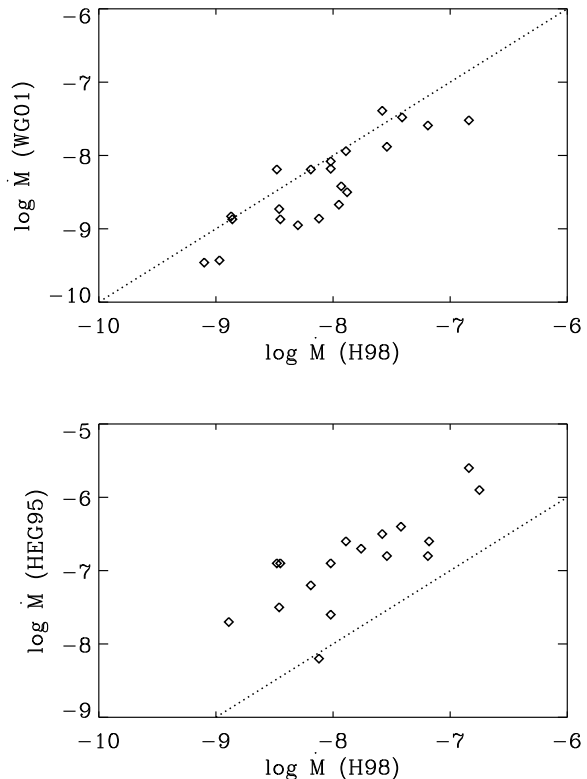


Figure 1. Comparison of stellar accretion rates (in $M_{\odot} \text{ yr}^{-1}$) from Hartmann et al. (1998) with those from White & Ghez (2001) (top panel, including only single stars) and Hartigan et al. (1995) (bottom panel). Note the systematic offsets in both cases, while the general trend with relatively small dispersion is maintained.

stellar masses than the D’Antona & Mazzitelli (1998) tracks used by H98. Meanwhile, the HEG95 values are higher on average by a factor of 8. This discrepancy, discussed in detail in G98, results from differences in extinction estimates, bolometric corrections, and the assumed accretion geometry. Based on these comparisons, we have scaled the values from WG01 up by a factor of 2 and the values from HEG95 down by a factor of 0.12 to place them on the same scale as H98.

Two objects, CoKu Tau/4 and UX Tau A, lack published UV measurements. We have thus estimated their stellar accretion rates using magnetospheric accretion models of H α profiles (e.g., Muzerolle, Calvet & Hartmann 2001 and references therein). The value for CoKu Tau/4 is an upper limit based on the line equivalent width since no resolved profiles exist in the literature. Based on the scatter in the Figure 1, we estimate that the resulting (random) uncertainty in the stellar accretion rates adopted here is likely to be less than a factor of ~ 3 or so, much less than the spread of ~ 100 in the stellar accretion rate at a given disc mass that is found in Taurus (§3).

2.3 Disk Masses

We adopted the disc masses (Table 1) estimated for Taurus sources based on submillimeter continuum measurements

(Andrews & Williams 2005). The data set has the advantage of being large and homogeneous. While Andrews & Williams (2005) estimated disc masses from SED fits where possible, the disc masses for most of the sample were determined from an empirical conversion between submillimeter fluxes and disc mass based on the SED fits. The random error in the disc masses is expected to be $\lesssim 0.5$ dex, primarily the result of the uncertainty in the spectral index at submillimeter wavelengths. Uncertainties in this range are much less than the two orders of magnitude spread in disc mass at a given stellar accretion rate that is found in Taurus (§3).

Systematic errors are also possible. For example, Hartmann et al. (2006) suggest that disc masses are likely to have been systematically underestimated because maximum grain sizes 3 – 10 times larger or smaller than 1 mm result in grain opacities significantly lower than is typically assumed. We can estimate the extent to which disc masses may be underestimated by looking at the upper end of the disc mass distribution reported by Andrews & Williams. Correction factors larger than 0.5 dex cannot be tolerated at the upper mass end without driving the disc masses over the theoretical gravitational instability limit. In any event, a demographic approach is robust against systematic errors in disk masses arising from under- or over-estimates of grain opacity, since systematic errors will shift demographic trends up or down in \dot{M}_{disc} but will not obscure them.

2.4 SED Classification

In Table 1, we provide a rudimentary classification of the observed SEDs of the Taurus sources based on ground-based photometry and mid-IR spectra from Spitzer/IRS (Furlan et al. 2006). Objects were classified as transition objects (T) if they show weak or no infrared excess shortward of $10\mu\text{m}$ and a significant excess at longer wavelengths. The initial selection and classification was made by visual inspection of the SED fits of Furlan et al. (2006). This resulted in our selecting objects whose excess emission fell by > 0.2 dex below that of the “Taurus Median” obtained from the analysis of all of the class II sources examined by D’Alessio et al. (1999). Systems with no significant infrared excess out to $\sim 30\mu\text{m}$, indicating no substantial disc material, were classified as “weak” objects (W). All other systems exhibit strong excess emission indicative of optically thick discs extending all the way in to the dust sublimation radius, either “classical” discs (C) or “flat-spectrum” (F) sources with elevated accretion rates and possible remnant envelopes.

Note that in several cases, the transition object classification may be influenced by the presence of unresolved companions with possible infrared excesses of their own. Also, for stars with lower masses, even “classical” discs can often exhibit lower excess emission at shorter wavelengths because the stellar irradiation flux, which is typically the dominant source of dust heating, is generally smaller. The likelihood of incorrectly classifying an object as “transition” as opposed to “classical” is thus greater among low mass, later spectral type stars owing to the decreased contrast between disc and photosphere. We therefore limit our analysis to stars with spectral types earlier than M3. We have indicated the remaining ambiguous cases in Table 1 (C?, T?, C/T). Table 2 captures the decrements from the Taurus median for all

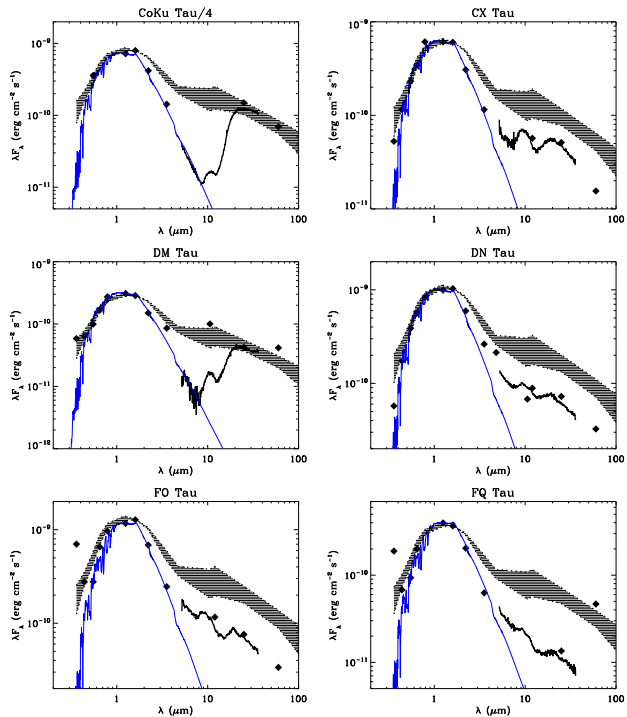


Figure 2. SEDs for all stars earlier than M3 that we identify as transition objects. Diamonds: optical and IRAS photometry from Kenyon & Hartmann (1995); near-infrared photometry from 2MASS; IRAC photometry from Hartmann et al. (2005). Black solid lines: IRS spectra from Furlan et al. (2006). Blue solid lines: Kurucz model photospheres of the appropriate spectral type, normalized to the dereddened J-band flux. Hashed region: the upper and lower quartiles of the Taurus CTTS median SED from D’Alessio et al. (1999).

sources that have a transition-like SED (i.e., sources with a T, T?, or C/T SED classification in Table 1).

Our classification scheme is broader than that adopted in some recent studies in which only systems with *no* apparent excess anywhere shortward of a given wavelength are considered to be transition objects (Muzerolle et al. 2006; Sicilia-Aguilar et al. 2006). We accept a broader range of excesses as transition objects, including those with weak excesses shortward of $10\mu\text{m}$, in order to avoid excluding systems in possibly interesting phases of planet formation. For example, systems that are dissipating their discs via photoevaporation are expected to have essentially no dust within R_{hole} and hence no excess above photospheric levels at short wavelengths. In contrast, a significant continuum excess might be expected from discs that have formed a Jovian mass planet and are replenishing, via accretion streams, an inner disc with gas and *dust* from an outer disc. In order to capture objects that are possibly in these states of evolution, we selected objects that show a significant decrement (≥ 0.2 dex) relative to the Taurus median SED.

3 RESULTS

Figure 3 plots the recalibrated stellar accretion rates from §2.2 against the disc masses described in §2.3. The top panel plots all sources for which detections are available for both

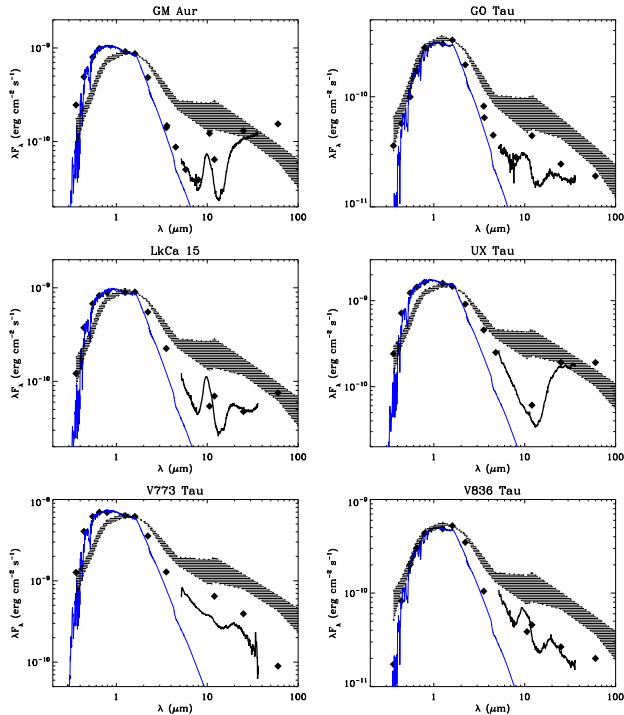


Figure 2. *continued* Additional SEDs for objects identified as transition objects.

axes. The subset of sources that are known binaries, with orbital separations $< 2.5''$ (Table 1), are shown as gray-brown filled points (White & Ghez 2001; Prato et al. 2002; Mathieu, Martín & Magazzu 1996; and references therein). The submillimeter observations do not resolve the binaries, so the reported fluxes may contain contributions from circumstellar disks as well as a circumbinary disk. The presence of an orbiting stellar companion may have a significant impact on the disc properties, e.g., by truncating a disc and thereby both reducing the disc mass and altering the SED (Jensen, Mathieu & Fuller 1996). Indeed, the median disc mass for the binary population is $\log M_{\text{disc}} = -2.8$, lower than the median disc mass of $\log M_{\text{disc}} = -2.3$ for the entire sample shown. Since a binary companion introduces additional complexity and may obscure important trends that result from other physical processes, we exclude these systems from our analysis. The remaining filled black points indicate sources that have no known binary companion within $2.5''$.

In the lower panel, the non-binary systems are further divided into those that have a transition-like SED (crosses), as described in §2.4, and those that do not (filled black points). The sources with transition-like SEDs are: GO Tau, LkCa 15, DN Tau, DM Tau, GM Aur, V836 Tau, UX Tau A, and CX Tau in order of decreasing disc mass. The SEDs of GO Tau and DN Tau (Furlan et al. 2006) are similar to those of the well studied transition objects GM Aur and DM Tau in that they also lack strong infrared excesses at short wavelengths but have optically thick outer discs. This is also the case for V836 Tau, which was originally classified as a transition object by Strom et al. (1989; see also Padgett et al. 2006). UX Tau A is noted as a transition object by Furlan et al. (2006). LkCa 15 has an SED that indicates an inner disc “gap” of a few AU (Bergin et al. 2004).

The concentration of crosses toward the lower right region of the plot suggests that transition objects inhabit a restricted region of the \dot{M}_* vs. M_{disc} plane. The existence of identifiable demographic groups demonstrates that the random errors in stellar accretion rates and disc masses (§3.2 and 3.2) are apparently insufficient to obscure significant population trends. We can estimate statistically the likelihood that the transition objects represent a distinct population in terms of their disc masses and accretion rates. Figure 4 compares the distributions of stellar accretion rates (top) and disc masses (bottom) for transition objects (dashed histograms) and non-transition single stars (solid histograms). For sparse data of this kind, the two-sided KS test is a good way to estimate the likelihood that the two distributions are drawn from the same parent distribution. With this approach, we find that there is a less than 3% probability that the stellar accretion rates of the transition and non-transition objects are drawn from the same parent distribution. For the disc masses, there is a less than 12% probability that the disc masses of the transition and non-transition objects are drawn from the same parent distribution.

A more useful estimate would jointly compare the distributions in both \dot{M}_* and M_{disc} . A two-dimensional two-sided KS test that accounts for the distribution of the two samples in both quantities estimates that there is a less than 0.8% probability that the transition and non-transition objects are drawn from the same parent distribution. Thus, even with the limited data available at present, it appears that the transition objects represent a distinct population in terms of their stellar accretion rates and disc masses.

For the stellar accretion rates, the median of the distribution is $\log \dot{M}_* = -8.5$ for the transition objects and $\log \dot{M}_* = -7.6$ for the non-transition objects. For the disc masses, the median of the distribution is $\log M_{\text{disc}} = -1.6$ for the transition objects and $\log M_{\text{disc}} = -2.2$ for the non-transition objects. Thus, compared to non-transition single stars, transition objects are biased to lower stellar accretion rates and larger disc masses. We discuss the possible origin of these biases in §4.

The likelihood that transition objects represent a population distinct from other classical T Tauri stars has possible implications for our understanding of the large dispersion in the \dot{M}_* vs. M_{disc} plane. In simple disc models the disc accretion rate $\dot{M}_d \propto \nu \Sigma$ locally, where Σ is the disc mass surface density and $\nu = \alpha c_s H$ is the viscosity parametrized in terms of the sound speed c_s and the disc scale height H . If all discs have a similar sizes (e.g., outer disc radii) and radial mass distributions (e.g., in a steady accretion disc $\Sigma \propto r^{-1}$; Hartmann et al. 1998), Σ would be proportional to M_{disc} . If, in addition, the disc accretion rate equals the stellar accretion rate, we would expect $\dot{M}_* \propto M_{\text{disc}}$. In contrast, Figure 3 (top) shows considerable scatter with no apparent trend between the two quantities. The apparent lack of the expected correlation has been noted previously (e.g., Dullemond, Natta, & Testi 2006).

If the transition objects represent a distinct population whose stellar accretion rates have been modified downward from their initial values (see §4), this downward evolution can account for some of the dispersion in the \dot{M}_* vs. M_{disc} plane. To illustrate this, we show least absolute deviation fits to the distributions in Figure 3. In comparison to a minimized chi-square error criterion, least absolute deviation fits

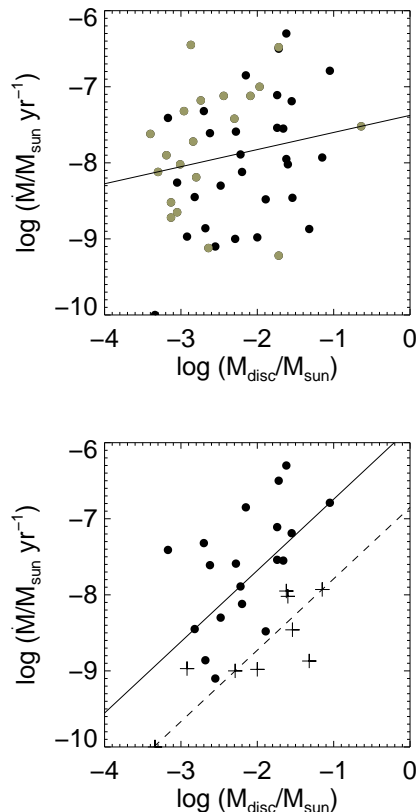


Figure 3. Stellar accretion rates and outer disc masses for sources in Taurus-Auriga. Top panel: systems possessing known a binary companion within 2.5'' (gray-brown points) have lower median disc masses compared to systems without such binary companions (black points). A least absolute deviation fit to all of the points shown gives a slope of 0.22 (solid line). Bottom panel: among the non-binary systems, those with transition-like SEDs (crosses) are segregated from those with non-transition SEDs (black points), with the transition objects having lower stellar accretion rates for their disc masses. Separately fitting the single, non-transition stars (solid line) and the transition objects (dashed line) gives a slope of 0.94 for each population. The upper limit to the accretion rate determined for CoKu Tau/4 is included in the fit for the transition objects.

are less sensitive to statistical outliers. In the top panel of Figure 3, a least absolute deviation fit to the \dot{M}_* vs. M_{disc} values for all sources for which there are detections in both axes gives a slope of 0.22, relatively far from the linear relation that would be expected in simple disc models.

If we remove the binaries from the sample (bottom panel) and fit separately the slopes of the the non-transition single stars (solid line) and the transition objects (dashed line), both populations have a slope of 0.94, close to the value of unity that would be expected if mass accretion rate is proportional to disc mass. The dashed line is offset downward from the solid line by approximately an order of magnitude, similar to the difference in the median accretion rates between the transition objects and the non-transition single stars. Because of the small number of sources that make up the transition object sample, the slope for that population is not well-determined.

4 DISCUSSION

We have found that transition objects in Taurus occupy a restricted region of the \dot{M}_* vs. M_{disc} plane. Compared to non-transition single stars in Taurus, they have stellar accretion rates that are typically ~ 10 times lower at the same disc mass. In addition, the median disc mass for the transition objects is ~ 4 times larger than the median disc mass for the non-transition single stars. The results place useful constraints on the possible explanations for the origin of the transitional SEDs in these systems. They also shed some light on the nature of the relation between disc masses and disc accretion rates. For example, the observed properties allow us to sort among the following proposed explanations for transitional SEDs.

(1) *Grain growth and the formation of rocky planetary cores in the inner disc* (e.g., Strom et al. 1989; Dullemond & Dominik 2005). If small grains are consumed in this process, the inner disc will become optically thin while remaining gas rich. As a result, the accretion rate through the disc and on to the star will continue unabated.

(2) *The dynamical clearing of a large gap by a Jovian mass planet* (e.g., Skrutskie et al. 1990; Marsh & Mahoney 1992; Calvet et al. 2002; Rice et al. 2003; D'Alessio et al. 2005; Calvet et al. 2005; Quillen et al. 2004). When a giant planet forms in a disc with a mass sufficient to open a gap, gap crossing streams, from the outer disc (beyond R_{hole}) to the planet, and from the planet to the inner disc (within R_{inner}), are expected to allow continued accretion on to both planet and star, the latter through the replenishment of an inner disc (Lubow, Seibert & Artymowicz 1999; see also Kley 1999; Bryden et al. 1999; D'Angelo, Henning, & Kley 2002; Bate et al. 2003; Lubow & D'Angelo 2006). By the time the planet is massive enough to open a gap, it is also able to divert a significant fraction of the mass accreting from the outer disc on to itself. Thus the stellar accretion rate is predicted to be reduced by a factor ~ 0.1 (Lubow & D'Angelo 2006) to ~ 0.05 (Varnière et al. 2006) compared to the mass accretion rate through the outer disc.

(3) *The isolation of the outer disc by a supra-Jovian mass planet, followed by the viscous draining of the inner disc.* As the planet grows in mass via accretion from the gap-crossing streams, accretion past the planet effectively ceases (Lubow et al. 1999), isolating the inner and outer disc. When the remaining inner disc material accretes on to the star, the system is left with a large inner hole, devoid of both gas and dust, and no further stellar accretion.

(4) *Disk photoevaporation.* Irradiation by energetic (UV and X-ray) photons from the star heat the disc surface layers to high temperatures $\sim 10^4$ K. Beyond a radius of ~ 7 –10 AU where the thermal velocity of the surface layers exceeds the escape speed ($\sim 10 \text{ km s}^{-1}$), a photoevaporative flow (characterized by a mass loss rate of $\sim 4 \times 10^{-10} M_{\odot} \text{ yr}^{-1}$; Hollenbach, Yorke & Johnstone 2000) is expected to develop. As discs viscously spread and accrete, eventually the column density of the outer disc drops sufficiently that the disc accretion rate becomes comparable to the disc photoevaporation rate. At this point, the region beyond the photoevaporation radius is losing material via photoevaporation more rapidly than it can resupply the inner disc through viscous accretion. The inner disc is thereby decoupled from the outer disc. Material in the inner disc accretes on to the star,

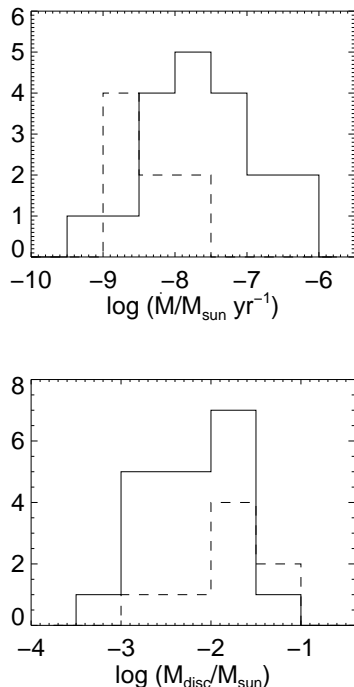


Figure 4. Comparison of the distributions of stellar accretion rates (top) and disc masses (bottom) for transition objects (dashed line) and single, non-transition stars (solid line) in the Taurus star forming region. Compared to single, non-transition stars, transition objects are biased to lower stellar accretion rates and larger disc masses.

leaving behind a large inner hole, devoid of gas and dust (the “UV Switch Model”; Clarke et al. 2001), producing a transitional SED.

When compared with these scenarios, the factor of ~ 10 decrement in the observed stellar accretion rates of transition objects compared to those of non-transition single stars at a given disc mass is remarkably similar to predictions for the Jovian mass planet formation scenario described above. The higher average disc masses for the transition objects, compared to those of non-transition single stars may also be consistent with this scenario since more massive discs are expected to be conducive to the formation of giant planets, either in the core accretion scenario (e.g., Lissauer & Stevenson 2006) or if gravitational instabilities play a role (e.g., Boss 2005; Durisen et al. 2005). These similarities are suggestive that the formation of Jovian mass planets plays a role in explaining the origin of at least some transitional SEDs in Taurus.

Indeed, for the Taurus transition objects with higher disc masses ($\gtrsim 0.01 M_{\odot}$), it is relatively straightforward to rule out the UV Switch model as an explanation for the transitional SEDs. The high disc masses of these systems imply large gas column densities at the gravitational radius, suggesting that photoevaporation can hardly be on the verge of decoupling the inner and outer discs. The stellar accretion rates of these sources ($10^{-9} - 10^{-8} M_{\odot} \text{ yr}^{-1}$) are in excess of the nominal disc photoevaporation rate of $4 \times 10^{-10} M_{\odot} \text{ yr}^{-1}$, further arguing against photoevaporation as the origin of the transitional SED. Since disk photoevaporation rates are

poorly known, sources with stellar accretion rates somewhat larger than the nominal $4 \times 10^{-10} M_{\odot} \text{ yr}^{-1}$ could be on the verge of clearing their inner disks. However, the inner disk is expected to clear rapidly once the stellar accretion rate drops down to the disk photoevaporation rate (Clarke et al. 2001); as a result, we would expect that few of the sources with stellar accretion rates of $\sim 10^{-9} M_{\odot} \text{ yr}^{-1}$ are passing through this brief evolutionary phase. The high disk masses of these transition objects ($\gtrsim 0.01 M_{\odot}$) support this interpretation. Similarly, large accretion rates ($10^{-9} - 10^{-8} M_{\odot} \text{ yr}^{-1}$) are not expected if these systems have formed a supra-Jovian mass planet. In contrast, significant accretion rates are expected when discs form planetesimals. However, unlike the presence of a Jovian mass planet, this mechanism does not provide a simple explanation for the low accretion rates of these objects for their disc masses.

The presence of an orbiting Jovian mass planet has indeed been the favored explanation for the SEDs of the Taurus transition objects GM Aur and DM Tau (Marsh & Mahoney 1992; Rice et al. 2003; Bergin et al. 2004; Calvet et al. 2005). If such a planet were present, with a mass large enough to reduce the accretion rate on to the star, we would infer artificially small values of α for the outer disc if we assumed that the accretion rate through the outer disc equalled the observed stellar accretion rate. Indeed, a low value of the viscosity parameter $\alpha \sim 0.001$ is inferred for DM Tau under this assumption (Calvet et al. 2005). Instead, if a Jovian mass planet is present, most of the mass accreting through the outer disc may accrete on to the planet rather than the star. If the outer disc accretion rate is then ~ 10 times the stellar accretion rate (Lubow & D’Angelo 2006), the inferred value of α characterizing the outer disc of DM Tau would be ~ 10 times larger, i.e., more similar to the value of $\alpha \simeq 0.01$ that is believed to be typical of T Tauri discs (Hartmann et al. 1998).

Notably, at least one of the transition objects in Taurus (CoKu Tau/4) has a disc mass ($\lesssim 10^{-3} M_{\odot}$) and a stellar accretion rate ($\lesssim 4 \times 10^{-10} M_{\odot} \text{ yr}^{-1}$) that are both low enough that its transitional SEDs may result from disc photoevaporation rather than giant planet formation. CX Tau is a possibly similar case, although its estimated disk mass and stellar accretion rate are somewhat larger than the above limits. While photoevaporation is not expected to erode away the inner regions of high mass discs ($\gtrsim 0.01 M_{\odot}$) until they are 6–15 Myr old (Clarke et al. 2001; Alexander et al. 2006), discs with sufficiently low initial masses can photoevaporate away on much shorter timescales, comparable to the age of Taurus. For example, scaling the standard accretion disc model of Hartmann et al. (1998) down in mass shows that a disc with $\alpha = 10^{-2}$ and $M_d = 10^{-3} M_{\odot}$ would spread beyond 100 AU and evolve to $\dot{M}_* < 3 \times 10^{-10} M_{\odot} \text{ yr}^{-1}$ on a time scale of ~ 1 Myr, a mass accretion rate low enough that photoevaporation would be able to create an inner hole.

If we interpret CX Tau and CoKu Tau/4 as systems whose SEDs are the result of photoevaporation, the remaining number of transition objects is roughly consistent with the interpretation that they are systems undergoing giant planet formation. The fraction of such transition objects is 7 out of a total of 28 non-binary T Tauri stars or 25%. This is larger than the 5–10% of nearby FGK stars currently known to harbor extrasolar giant planets. If the current detection statistics are extrapolated to 20 AU, the expected

fraction of planet-bearing systems rises to $\sim 12\%$ (Marcy et al. 2005). This is not totally inconsistent with the 25% fraction of transition objects identified here, given both the small sample of objects studied and the possible role of planetary orbital migration in accounting for any difference in the incidence rates of accreting transition objects and extra-solar giant planets.

Perhaps surprisingly, there is a dearth of transition objects intermixed with the population of non-transition, single stars. Systems that are forming planetesimals and protoplanets (i.e., objects too low in mass to open a gap) would be expected to occupy this region of the diagram. That is, they would appear as systems with optically thin inner discs but otherwise unaltered stellar accretion rates. Perhaps the lack of such systems indicates that planetesimal and protoplanet formation is inefficient in clearing the dust from the inner regions of accreting discs (cf. Dullemond & Dominik 2005). This might be the case if the accretion of small dust grains from larger disk radii is effective in “filling in” the opacity holes created by grain growth at smaller radii. Alternatively, the phase of planetesimal and protoplanet formation may be very short-lived.

A tempting counter-hypothesis is that systems that have experienced significant grain growth and settling (and are forming planetesimals and protoplanets) are intermixed with the transition objects we have identified as candidate giant-planet forming systems. This might explain the diversity of transition object SEDs (Figure 2) that range from those with large “dips” (e.g., GM Aur) to “anemic” SEDs (e.g., GO Tau) that might be more characteristic of systems that have undergone grain settling and growth. However, as already noted, it is difficult to understand why systems that have experienced significant grain growth would show lower accretion rates for their disk masses. By reducing the small grain population in the surface layers of the disk, grain growth is expected to lead to larger ionization fractions and therefore larger surface disk columns that are susceptible to the magnetorotational instability (e.g., Sano et al. 2000). We would then naively expect that such disks would have *larger* accretion rates for their disk masses, rather than the reduced accretion rates that are observed. Whether or not this is in fact the case, we may be able to determine observationally whether transition objects produced via grain growth are intermixed with systems that have formed giant planets, by measuring the radial distribution of gas in the disk. The radial distribution of gas would be continuous for the grain growth scenario, whereas it would show a radial gap if a Jovian mass planet has formed.

Finally, we note that if we interpret the transition objects as systems in which the stellar accretion rate has been reduced from its original value (either by the presence of a giant planet or by photoevaporation) so that the accretion rate on to the star no longer traces the outer disc accretion rate, this implies a reduced scatter in the relation between disc mass and accretion rate. If we consider only the single, non-transition stars as the systems in which the stellar accretion rate might more closely trace the *disc* accretion rate (Figure 3, bottom), the range in \dot{M}_* at a given M_{disc} is reduced by a factor of ~ 3 compared to the range when the transition objects are included.

By considering only single, non-transition objects, the relation between disc mass and stellar accretion rate has

steeper a slope compared to that in Figure 3 (top), quite close to the expected value of unity. There are many potential explanations for the remaining scatter. Disks may have substantial dead zones that do not participate in accretion (Gammie 1996). Disk grain opacities may evolve (D’Alessio et al. 2006; Natta et al. 2006), or the dust content that is measured by the submillimeter continuum may not reliably trace the gas (Takeuchi & Lin 2005). Alternatively, the viscosity parameter α may not be a constant from star to star, or discs may possess a range of initial angular momenta (Hartmann et al. 1998; Dullemond et al. 2006).

One potential problem with the interpretation that the transition objects with higher disc masses have formed Jovian mass companions is that their SEDs do not appear to show the distinctive “gap” structure one expects if a Jovian mass planet is present. Several of these sources (GM Aur, DM Tau) have been fit with little to no dust in the inner disc (e.g., Calvet et al. 2005), in marked contrast to the highly optically thick inner disc (within $R_{\text{inner}} < R_{\text{hole}}$) that would be expected for transition objects with T Tauri-like accretion rates of $10^{-9} - 10^{-8} M_{\odot} \text{ yr}^{-1}$. This conundrum suggests the importance of developing a deeper understanding of the processes that affect the vertical distribution of grains in the outer disk, the transport of grains from the outer to the inner disc, as well as the transformation of grain properties in the inner disc (e.g., grain growth, destruction in spiral shocks) in order to use SEDs as a finely honed tool for distinguishing among the possibly physical origins of a transition SED.

Rice et al. (2006) have suggested that the filtering of grains at gap edges can help to explain the lack of dust opacity in the inner disc (within R_{inner}). As they describe, gas-grain coupling may drive grains larger than $1\text{--}10\mu\text{m}$ away from the gap edge allowing only a small fraction of the solid mass to accrete past R_{hole} . Such a mechanism will reduce the amount of solids reaching both the inner disc and the planet in this stage of evolution. As an additional mechanism, the high grain densities that arise as material from the outer disc is concentrated into narrow accretion streams may also give rise to rapid grain growth and a further reduction in the disc opacity. Similarly, the possible presence of a dead zone (Gammie 1996) in the outer disc, combined with grain growth and settling out of the surface regions of the disk (i.e., the region undergoing accretion), may also reduce the mass of small grains reaching R_{hole} . A dead zone has been invoked, similarly, by Ciesla (2006) in the context of *non*-accreting disks, where a transition-like SED may be produced in disks that have experienced significant grain growth but have not formed giant planets.

An additional potential problem with the interpretation that the transition objects with higher disc masses have formed Jovian mass companions is that the mass doubling time for the putative accreting planet is quite short. The median stellar accretion rate for these systems is $\sim 3 \times 10^{-9} M_{\odot} \text{ yr}^{-1}$, which for a planetary accretion rate 10 times larger implies a mass doubling time of 0.03 Myr, an interval short compared to the ~ 1 Myr age of Taurus. Such a mass accretion timescale might be consistent with the observed fraction of transition objects if sources in Taurus are approximately coeval, giant planet formation is common, and it takes close to 1 Myr to form a planet massive enough to open a gap. Alternatively, other processes for forming transition disks may be at work. If so, they must

provide a natural explanation for the apparent tendency for transition objects to have large disk masses and low stellar accretion rates.

Given these uncertainties, it would be useful to identify additional ways of confirming the presence of a giant planet beyond the modeling of SEDs. Perhaps one of the most convincing approaches would be to search for direct evidence of the presence of such a planet. If the stellar accretion rate in these systems is ~ 0.1 of the outer disc accretion rate, the planet then accretes at a high rate, ~ 9 times the stellar accretion rate, making the planet easier to detect. Among the transition objects in Taurus, GM Aur is the most promising system for such a search because of the potentially large separation between the planet and star (~ 20 AU or $0.13''$). It also has a large accretion rate. The stellar accretion rate of $10^{-8} M_{\odot} \text{ yr}^{-1}$ implies an accretion rate of $\sim 9 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$ on to the planet. Extrapolating from the calculations of Hubickyj, Bodenheimer & Lissauer (2005) and Papaloizou & Nelson (2005), the accretion luminosity of the planet is expected to be substantial, $\sim 0.02 L_{\odot}$. The resulting modest contrast ratio between the accreting planet and the central star may greatly facilitate the detection of such an object.

5 SUMMARY

Using the approach introduced here, a study of the demographics of accreting T Tauri stars, we find that transition objects inhabit restricted regions of the \dot{M}_{*} vs. M_{disc} plane. Compared to non-transition single stars in Taurus, they have stellar accretion rates that are typically ~ 10 times lower at the same disc mass. In addition, the median disc mass for the transition objects is ~ 4 times larger than the median disc mass for the non-transition single stars. The decrement in the stellar accretion rates and the higher average disc masses are suggestive that the formation of Jovian mass planets plays a role in explaining the origin of some transitional SEDs in Taurus.

For the transition objects with higher disc masses ($\gtrsim 0.01 M_{\odot}$), it seems plausible that a Jovian mass planet has created a large gap and suppressed the accretion rate on to the star (Lubow & D'Angelo 2006; Varnière et al. 2006). The high accretion rate $\sim 9 \dot{M}_{*}$ inferred for the Jovian mass planets in these systems would make an accreting giant planetary companion easier to detect using either direct imaging or through infrared interferometry. The remaining transition objects have the low disc masses $\lesssim 0.001 M_{\odot}$ expected for discs that have cleared inner holes through photoevaporation. In contrast, the paucity of sources with stellar accretion rates and disc masses similar to those of non-transition, single T Tauri stars leads us to question the formation of planetesimals or low mass protoplanets as a likely pathway to a transitional SED. Planetesimal or low mass protoplanet formation may be unable to completely remove small dust grains from the disc; alternatively, this phase of evolution may be very short-lived.

Accreting transition objects that arise as a consequence of the formation of either planetesimals or a Jovian mass planet present a significant theoretical challenge: how to sustain an optically thin inner region while accreting material from a dusty outer disc. Understanding the physical mech-

anisms that can sustain an optically thin inner region in an accreting transition disc represents a critical step toward understanding the evolutionary state of these objects.

Finally, considering transition objects as a distinct demographic group among accreting T Tauri stars, whose stellar accretion rates have been altered as a consequence of either giant planet formation or disc photoevaporation, leads to a tighter relation between disc masses and stellar accretion rates, with a slope between the two quantities that is close to the value of unity expected in theories of disc accretion. These results, while suggestive, are based on a small sample of objects. Future observations aimed at determining disc masses, stellar accretion rates, and SEDs for large samples of T Tauri stars will be critical in improving our understanding of the demographics and nature of transition objects.

ACKNOWLEDGMENTS

We are grateful to Lee Hartmann, Nuria Calvet, Doug Lin, and Geoff Bryden for stimulating and insightful discussions on this topic. We also thank the anonymous referee for thoughtful comments that improved the manuscript.

REFERENCES

- Alexander R. D., Clarke C. J., Pringle J. E. 2006, MNRAS, 369, 229
- Andrews S. M., Williams J. P. 2005, ApJ, 631, 1134
- Baraffe I., Chabrier G., Allard F., Hauschildt P. H. 1998, A&A, 377, 403
- Bate M. R., Lubow S. H., Ogilvie G. I., Miller K. A. 2003, MNRAS, 341, 213
- Bergin E., et al. 2004, ApJ, 614, L133
- Boss A. P. 2005, ApJ, 629, 535
- Bryden G., Chen X., Lin D. N. C., Nelson R. P., Papaloizou J. C. B. 1999, ApJ, 514, 344
- Calvet N., D'Alessio P., Hartmann L., Wilner D., Walsh A., Sitko M. 2002, ApJ, 568, 1008
- Calvet N., Muzerolle J., Briceño C., Hernández J., Hartmann L., Saucedo J. L., Gordon K. D. 2004, AJ, 128, 1294 (C04)
- Calvet N., et al. 2005, ApJ, 630, L185
- Ciesla, F. J. 2006, ApJ, in press (astro-ph/0611811)
- Clarke C. J., Gendrin A., Sotomayor M. 2001, MNRAS, 328, 485
- D'Alessio P., Calvet N., Hartmann L., Lizano S., Cantó J. 1999, ApJ, 527, 893
- D'Alessio P. et al. 2005, ApJ, 621, 461
- D'Alessio P., Calvet N., Hartmann L., Franco-Hernández R., Servín H. 2006, ApJ, 638, 314
- D'Angelo G., Henning T., Kley W. 2003, ApJ, 599, 548
- D'Antona F., Mazzitelli I. 1998, in R. Rebolo, E. L. Martín, M. R. Zapatero Osorio, eds, ASP Conf. Ser. 134, Astron. Soc. Pac., San Francisco, p. 442
- Dullemond C. P., Dominik C. 2005, A&A, 434, 971
- Dullemond C. P., Natta A., Testi L. 2006, ApJ, 645, L69
- Durisen R. H., Cai K., Mejía A. C., Pickett M. K. 2005, Icarus, 173, 417
- Furlan E., et al. 2006, ApJS, 165, 568

- Gammie C. F. 1996, *ApJ*, 457, 355
- Gauvin L. S., Strom K. M. 1992, *ApJ*, 385, 217
- Gullbring E., Hartmann L., Briceño C., Calvet N. 1998, *ApJ*, 492, 323 (G98)
- Gullbring E., Calvet N., Muzerolle J., Hartmann L. 2000, *ApJ*, 544, 927 (G00)
- Hartigan P., Edwards S., Ghandour L. 1995, *ApJ*, 452, 736 (HEG95)
- Hartmann L., Calvet N., Gullbring E., D'Alessio P. 1998, *ApJ*, 495, 385 (H98)
- Hartmann L., Megeath S. T., Allen L., Luhman K., Calvet N., D'Alessio P., Franco-Hernandez R., Fazio G. 2005, *ApJ*, 629, 881
- Hartmann L., D'Alessio P., Calvet N., Muzerolle J. 2006, *ApJ*, 648, 484
- Hollenbach D. J., Yorke H. W., Johnstone D. 2000, in Mannings, V., Boss, A. P., Russell, S. S., eds, *Protostars and Planets IV*, University of Arizona, Tucson, p. 401
- Hubickyj O., Bodenheimer P., Lissauer J. J. 2005, *Icarus*, 179, 415
- Jensen E. L. N., Mathieu R. D., Fuller G. A. 1996, *ApJ*, 458, 312
- Kenyon S. J., Hartmann L. 1995, *ApJS*, 101, 117
- Kley W. 1999, *MNRAS*, 303, 696
- Lissauer J. J., Stevenson D. J. 2006, in B. Reipurth, ed, *Protostars and Planets V*, University of Arizona Press, Tucson, in press
- Lubow S. H., Seibert M., Artymowicz P. 1999, *ApJ*, 526, 1001
- Lubow S. H., D'Angelo G. 2006, *ApJ*, 641, 526
- Marcy G., Butler R. P., Fischer D., Vogt S., Wright J. T., Tinney C. G., Jones H. R. A. 2005, *Prog. Theor. Phys. Supp.*, 158, 2005
- Marsh K. A., Mahoney M. J. 1992, *ApJ*, 395, L115
- Mathieu R. E., Martín E. L., Magazzu A. 1996, *BAAS*, 188, 60.05
- McCabe C., Ghez A. M., Prato L., Duchêne G., Fisher R. S., Telesco C. 2006, *ApJ*, 636, 932
- Muzerolle J., Calvet N., Hartmann L. 2001, *ApJ*, 550, 944
- Muzerolle J., Hillenbrand L., Calvet N., Briceño C., Hartmann L. 2003, *ApJ*, 592, 266
- Muzerolle J., et al. 2006, *ApJ*, 643, 1003
- Natta A., Testi L., Muzerolle J., Randich S., Comerón F., Persi P. 2004, *A&A*, 424, 603
- Natta A., Testi L., Calvet N., Henning T., Waters R., Wilner D. 2006, in B. Reipurth, ed, *Protostars and Planets V*, University of Arizona Press, Tucson, in press
- Padgett D. L., et al. 2006, *ApJ*, 645, 1283
- Palla F., Stahler S. 1999, *ApJ*, 525, 772
- Papaloizou J. C. B., Nelson R. P. 2005, *A&A*, 433, 247
- Prato L., Simon M., Mazeh T., McLean I. S., Norman D., Zucker S. 2002, *ApJ*, 569, 863
- Quillen A. C., Blackman E. G., Frank A., Varnière P. 2004, *ApJ*, 612, L137
- Rice W. K. M., Wood K., Armitage P. J., Whitney B. A., Bjorkman J. E. 2003, *MNRAS*, 342, 79
- Rice W. K. M., Armitage P. J., Wood K., Lodato G. 2006, *astro-ph/0609808*
- Sano, T., Miyama, S. M., Umebayashi, T., Nakano, T. 2000, *ApJ*, 543, 486
- Sicilia-Aguilar A., et al. 2006, 638, 897
- Skrutskie M. F., Dutkevitch D., Strom S. E., Edwards S., Strom K. M., Shure M. A. 1990, *AJ*, 99, 1187
- Strom K. M., Strom S. E., Edwards S., Cabrit S., Skrutskie M. F. 1989, *AJ*, 97, 1451
- Takeuchi T., Lin D. N. C. 2005, *ApJ*, 623, 482
- Varnière P., Blackman E. G., Frank A., Quillen A. C. 2006, *ApJ*, 640, 1110
- White R. J., Ghez A. M. 2001, *ApJ*, 556, 265 (WG01)
- White R. J., Hillenbrand L. A. 2004, *ApJ*, 616, 998
- Wolk S. J., Walter F. M. 1996, *AJ*, 111, 2066

Table 1. Taurus-Auriga Stellar Accretion Rates and Disk Masses.

Name	Spectral Type	Binarity ^a	SED ^b	$\log \dot{M}_*$ ^c	\dot{M}_* Ref.	$\log M_d$ ^d
AA Tau	K7	S	C	-8.48	G98	-1.89
Anon 1	M0	S	W	<-8.56	WG01	<-3.40
BP Tau	K7	S	C?	-7.54	G98	-1.74
CI Tau	K7	S	C	-7.19	H98	-1.55
CoKu Tau/4	M1.5	X	T	<-10	^e	-3.34
CW Tau	K3	S	C	-7.61	WG01	-2.62
CX Tau	M2.5	S	T	-8.97	H98	-2.92
CY Tau	M1	S	C	-8.12	G98	-2.20
DD Tau A	M1	B	C	-8.72	WG01	-3.13
DE Tau	M2	S	C	-7.59	G98	-2.28
DF Tau A	M0.5	B	C	-7.62	WG01	-3.40
DG Tau	K7-M0	S	F	-6.30	G00	-1.62
DH Tau	M1	S	C	-8.30	H98	-2.48
DK Tau	K7	B	C	-7.42	G98	-2.30
DL Tau	K7	S	C	-6.79	WG01	-1.05
DM Tau	M1	S	T	-7.95	H98	-1.62
DN Tau	M0	S	C/T	-8.46	G98	-1.54
DO Tau	M0	S	C/F	-6.85	G98	-2.15
DP Tau	M0	S	C/F	-7.88	H98	<-3.30
DQ Tau	M0	B	C	-9.22	G98	-1.72
DR Tau	K7	S	F	-6.50	G00	-1.72
DS Tau	K5	S	C	-7.89	G98	-2.22
FM Tau	M0	S	C	-8.45	H98	-2.82
FO Tau A	M2	B	T?	-7.90	WG01	-3.19
FQ Tau	M2	B	T?	-6.45	H98	-2.87
FS Tau	M1	B	C/F	-9.12	WG01	-2.64
FV Tau A	K5	B	C	-7.32	WG01	-2.96
FX Tau	M1	B	C	-8.65	H98	-3.05
FY Tau	K7	S	X	-7.41	H98	-3.17
FZ Tau	M0	S	C	-7.32	WG01	-2.70
GG Tau Aa	K7	B	C	-7.52	WG01	-0.64
GH Tau A	M2	B	C	-8.52	WG01	-3.13
GK Tau	K7	B	C	-8.19	G98	-2.80
GM Aur	K3	S	T	-8.02	G98	-1.60
GO Tau	M0	S	C/T	-7.93	H98	-1.15
Haro 6-37	K6	B	C	-7.00	H98	-1.97
HBC 376	K7	S	X	<-8.92	WG01	<-3.54
HBC 388	K1	S	W	<-8.03	WG01	<-3.49
HO Tau	M0.5	S	C	-8.86	H98	-2.68
Hubble 4	K7	S	W	<-7.78	WG01	<-3.36
IP Tau	M0	S	C	-9.10	G98	-2.55
IQ Tau	M0.5	S	C	-7.55	H98	-1.66
IS Tau A	K7	B	C	-7.72	WG01	-2.84
L1551-51	K7	S	W	<-9.12	WG01	<-3.19
L1551-55	K7	S	X	<-9.32	WG01	<-3.56
LkCa 14	M0	S	X	<-8.47	WG01	<-3.35
LkCa 15	K5	S	C/T	-8.87	H98	-1.32
LkCa 19	K0	S	X	<-9.62	WG01	<-3.30
LkCa 4	K7	S	W	<-8.35	WG01	<-3.70
LkCa 5	M2	S	W	<-9.62	WG01	<-3.72
RW Aur A	K3	B	C	-7.12	WG01	-2.44
RY Tau	G1	S	C	-7.11	C04	-1.74
SU Aur	G1	X	C	-8.26	C04	-3.05
T Tau A	G6	B	F	-7.12	WG01	-2.09
UX Tau A	K2	S	T	-9.00	^f	-2.29
UY Aur	K7	B	C	-7.18	G98	-2.74
UZ Tau E	M1	B	C	-6.48	VBJ93	-1.72
V410 Tau A	K3	B	W	<-8.42	WG01	<-3.44

Table 1 – *continued* Taurus-Auriga Stellar Accretion Rates and Disk Masses.

Name	Spectral Type	Binarity ^a	SED ^b	$\log \dot{M}_*^c$	\dot{M}_* Ref.	$\log M_d^d$
V773 Tau	K3	B	C/T	<-9.62	WG01	-3.33
V807 Tau A	K7	B	X	-8.02	WG01	-3.01
V819 Tau	K7	S	W ^g	<-8.48	WG01	<-3.35
V827 Tau	K7	S	W	<-8.15	WG01	<-3.50
V836 Tau	K7	S	T?	-8.98	HEG95	-2.00
V955 Tau	K7	B	C	-8.12	WG01	-3.30

^a Binarity where S=single; B=binary with orbital separation < 2.5'';

^b SED class where C=classical T Tauri star; F=extremely active accretor or flat spectrum source; T=transition object, i.e., no IR excess shortward of 10 μ m and a significant excess at longer wavelengths; W=optically thin or no IR excess shortward of 30 μ m; X=unknown. Entries with a C?, T? or c/T indicate uncertainty in the true level of the short-wavelength IR excess either because of variability (e.g., BP Tau, V836 Tau) or companions (e.g., V773 Tau). These designations are also used in cases of ambiguity between a transition phenomenon and naturally lower near-IR excess emission around later-type stars where the irradiation flux impinging on the disc is smaller (e.g., FO Tau, FQ Tau, GO Tau).

^c Stellar accretion rate in units of $M_\odot \text{ yr}^{-1}$.

^d Disk masses in units of M_\odot from Andrews & Williams (2005).

^e \dot{M}_* upper limit estimated assuming no accretion component is measurable at H α .

^f \dot{M}_* estimated from an accretion model of the H α profile shown in Alencar & Basri (2000).

^g Furlan et al. (2006) note that a 2MASS companion with unknown mid-infrared properties, which also lay in the long-low slit, possibly accounts for the longer wavelength excess in the measured SED.

Table 2. SED Decrements of Transition Objects.

Name	SED	$\Delta_{3.5}$ dex	$\Delta_{5.0}$ dex
CoKu Tau/4	T	0.4	0.7
CX Tau	T	0.4	0.3
DM Tau	T	0.2	>0.3
DN Tau	C/T	0.2	0.1
GM Aur	T	0.5	0.4
FO Tau A	T?	0.25	0.15
FQ Tau	T?	0.4	0.3
GO Tau	C/T	0.3	0.25
LkCa 15	C/T	0.2	0.2
UX Tau A	T	0.15	0.25
V773 Tau	C/T	0.35	0.25
V836 Tau	T?	0.35	0.05